Return to Session

SENSITIVITY OF PD INCEPTION TO CHANGE OF ELECTRICAL DESIGN IN POLYMERIC INSULATED POWER CABLE SYSTEMS

Peter VAN DER WIELEN, KEMA TDT, (The Netherlands), Peter.vanderWielen@kema.com
Nico VAN SCHAIK, KEMA TDT, (The Netherlands), Nico.vanSchaik@kema.com
Tadeusz CZASZEJKO, Monash University, (Australia), Tadeusz.Czaszejko@eng.monash.edu.au

ABSTRACT

A methodology was developed to calculate the partial discharge inception voltage in MV, HV and EHV cable systems for different electrical designs. By doing so, the sensitivity of the PD inception voltage to change in design of the insulation system can be defined and quantified. As the result, the effect on the change of the acceptable maximum size on potential defects may be estimated, indicating the increase of risk on PD inception when changing the design. The methodology and calculations presented quantified the extend to which the quality of the extrusion process as well as the precision of accessories assembly must be maintained or improved to assure discharge free operation of cable systems after design modifications. They also show that margins specified in the range of type approval in the current IEC standards are sufficient and that they should not be broadened.

KEYWORDS

Partial discharge, inception voltage, power cables, XLPE insulation, design modifications, voids, fissures.

INTRODUCTION

The insulation of power cables and their accessories has to be able to withstand electrical fields of high magnitude. Small impurities, voids or fissures distort this electrical field and can cause small, partial, discharges to occur if the local electrical field becomes higher than the local breakdown strength. Partial discharges (PDs) themselves cause further deterioration of the insulation material and therefore shorten the lifetime considerably. Discharge-free operation of power cable systems is therefore paramount to a safe and long operation lifetime of power cable systems.

To verify the insulation integrity, international standards, such as IEC60502, IEC60840 and IEC62067, as well as national standards describe the required set of pre-qualification and type tests. Tests like this are essential for safe and reliable operation of HV equipment. But inevitably, with every kind of test there are time and costs involved. Therefore, the standards also include a range of type approval, where the ranges of the applicable design parameters are defined for which the tests of only one variant are valid. From this, the question has arisen whether the range of allowable dimension variations can be widened further in order to reduce the amount of testing associated with a new design. For this reason, CIGRÉ Working Group B1-06 was formed in 2002 with the task to revise these ranges of approval.

If the dimensions of a power cable change, the electrical field strength will also change, and with this the risk on PDs. An important aspect of the investigation of the CIGRÉ Working Group B1-6 was therefore to investigate the influence of dimensional change on the risk of PD occurrence. Specific recommendations resulting from this analysis were published by CIGRÉ [1]. The aim of this paper is to present a systematic analytical approach developed for this purpose.

The topic of the mechanisms of partial discharges in solid dielectrics is well covered in literature, however, few articles refer directly to partial discharge inception in high voltage cable insulation. Three-phase belted cables pose special challenges in this respect. This is addressed in [2] with the focus on PD excitation, the induced voltages on the surrounding conductors resulting from PDs and their resulting detectability. The PD inception voltage in single-core cables with radial electrical field in the insulation was investigated in [3] and [4], focussing on conditions for discharge-free operation itself. Generally, and these two papers serve as an example, such work is done by either computer simulations or focussing on a narrow range of power cables from one specific class.

To enable such analysis to apply over the entire range of practical cable designs, we have developed a methodology based not only on absolute values of dimensions, electric stresses and breakdown voltages, but added sensitivity relations between these parameters. These sensitivity parameters allow a clear view on how varying a particular design parameter would influence all the others. This paper uses this methodology to relate the dimensional change to the maximum defect size allowed for a discharge-free operation. This relationship is demonstrated for a range of practical cable dimensions with some examples given. The methodology is valid for the complete range of MV, HV as well as EHV single-core power cables.

ELECTRICAL STRESSES IN POWER CABLES

We restrict our analysis to concentric electrical fields found in screened single-core power cables, which form the majority of installed cable population. An interesting study of electrical field distribution and partial discharge propagation in three-phase belted cables can be found in [2].

The electric field intensity E_x at a radial location x in a concentric cable is expressed by a well known formula

$$E_x = \frac{U_0}{x \ln \frac{R}{r}} \qquad (1)$$

where r and R are the radii of the conductor and the insulation shield respectively and U_0 is the voltage between conductor and shield. In order to determine the range of the electric field intensity, and subsequently its sensitivity to dimensional change, we need to examine the range of cable dimensions found in practice.

Insulation thickness w varies in accordance with cable voltage rating and its values are recommended by international standards. As an example, IEC60502-2 prescribes the insulation thickness for MV cables. With the help of such standards, the manufacturer usually determines the insulation thickness from the design electrical stress. In this paper, we assume the lower limit of the usual insulation thickness to be 3.4 mm, which relates to a 6/10 kV rating. We take 30 mm to be the upper limit of insulation thickness. This corresponds with a 220/400 kV rating, although also slimmer designs are known to exist at this voltage level.
The range of conductor sizes, and thus the insulation inner radius r, varies in each voltage rating. The smallest conductor sizes are found in MV cables where a typical range of conductor cross-section area is between 10 mm^2 and 1000 mm^2. This translates to the conductor diameter range of approximately 5 – 40 mm. We will concentrate on the recommended 50 mm^2 and above. At the other end of the voltage-rating spectrum, the typical range for EHV cables is from 630 mm^2, or 30 mm in diameter, to 2500 mm^2, or 60 mm in diameter. IEC60228 gives the exact minimum and maximum dimensions for the range of cross sections with stranded and solid conductors. In the following parts of this paper, the recommended size ranges of this standard are used.
As is clear from the above, the optimal ratio of R to r derived in many textbooks, which is equal to the natural number e, is purely theoretical. Since the dimensions r and w are the independent parameters, determined by the ampacity and the voltage level respectively, the insulation outer radius R is usually just the result of that and therefore not independent. The given range of practical dimensions allows a complete set of electrical stress levels on the conductor screen, E_r, and on the insulation screen interface, E_R, to be calculated. Figure 1 shows the resulting minimal and maximal stress levels for cables in all rated voltage categories from 10 kV up to 400 kV.

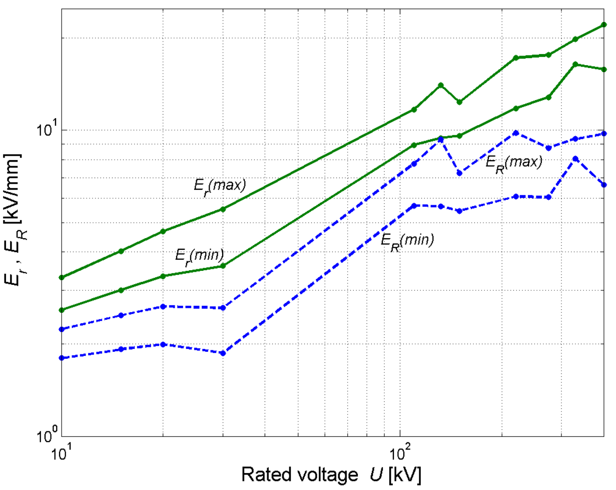

Figure 1: Range of electrical stress levels for practical high voltage cable designs (conductor sizes according to IEC60228)

SENSITIVITY OF ELECTRIC STRESS TO VARIATION OF CABLE DIMENSIONS

To determine the extent to which variations in cable dimensions influence electric stress, we define the electric stress sensitivity as the rate of change of field strength with respect to the variation of the given dimension. To enable a more general analysis, we represent the electric stress sensitivity as a value relative to the relevant nominal field intensity, E_r and E_R, and relative to the relevant dimensions, r and w.

Sensitivity to variation of inner radius

The derivative of field intensity with respect to the inner radius, r, gives the desired sensitivities at the two locations: on the inner insulation surface, dE_r/dr, and on the outer insulation surface, dE_R/dr. The relative sensitivities are as follows:

$$SD_{r,r} = \frac{dE_r/E_r}{dr/r} = \frac{w}{r+w}\frac{1}{\ln\frac{r+w}{r}} - 1 \qquad (2)$$

$$SD_{R,r} = \frac{dE_R/E_R}{dr/r} = \frac{r}{r+w}\left(\frac{w}{r}\frac{1}{\ln\frac{r+w}{r}} - 1\right) \qquad (3)$$

It can be seen that the sign of $SD_{r,r}$, equation (2), is negative, indicating that an increase of the inner conductor radius, with a constant insulation thickness, will result in a decrease of the dielectric stress on the conductor screen interface. The sign of $SD_{R,r}$, equation (3), is positive, indicating that an increase of the conductor size, with constant w, will always result in an increase of the dielectric stress on the insulation screen interface. All as expected. The sensitivity functions are plotted in Figure 2.

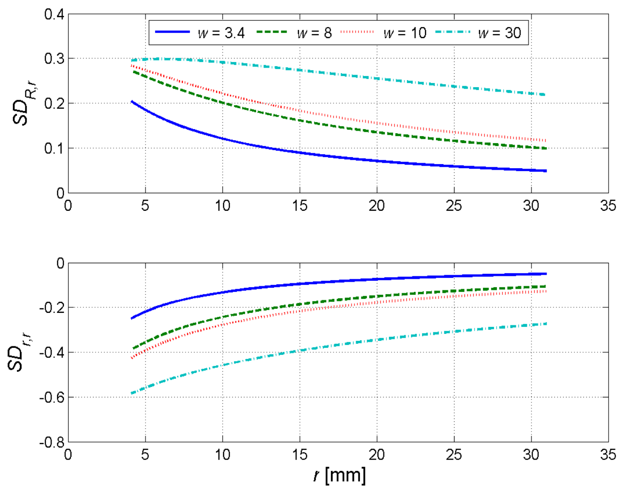

Figure 2: Relative electric stress sensitivity at the insulation screen interface ($SD_{R,r}$) and at the conductor screen interface ($SD_{r,r}$) as a function of the conductor radius

The (absolute values of the) relative sensitivities of the electrical stress to variation of the conductor radius at both locations increase with insulation width w and decrease with conductor radius. This means that maximum influence of the change of conductor radius on the electrical stress occurs at small conductor sizes and/or higher voltages.

Sensitivity to variation of insulation thickness

Analogue to the derivation of the sensitivities to conductor radius, the following relations can be obtained for the relative sensitivities of the electrical stress to variations in insulation thickness:

$$SD_{r,w} = \frac{dE_r/E_r}{dw/w} = -\frac{w}{r+w}\frac{1}{\ln\frac{r+w}{r}} \qquad (4)$$

$$SD_{R,w} = \frac{dE_R/E_R}{dw/w} = -\frac{w}{r+w}\left(\frac{1}{\ln\frac{r+w}{r}}+1\right) \qquad (5)$$

The negative signs in both equations reveal, as expected, that every increase in insulation thickness, with constant conductor radius, will always result in a decrease of electrical stress at both the conductor and the insulation screen. In Figure 3 both functions are plotted.

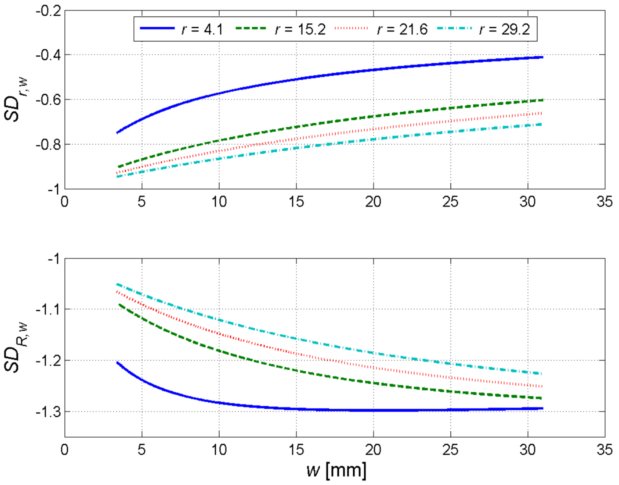

Figure 3: Relative electric stress sensitivity at the insulation screen interface ($SD_{R,w}$) and at the conductor screen interface ($SD_{r,w}$) as a function of the insulation width *w*

The (absolute value of the) relative sensitivity of the electrical stress at the conductor screen to variation of the insulation width $SD_{r,w}$ decreases with insulation width and increases with conductor size. For this relative sensitivity at the insulation screen $SD_{R,w}$ we see an increase with insulation width and an decrease with conductor size.

From Figure 2 and Figure 3 we can also see that the electric field intensity depends to a greater degree on the change of insulation thickness ($SD_{(R,r),w}$) than on the change of conductor size ($SD_{(R,r),r}$). This is especially pronounced for the electrical field at the insulation screen E_R.

As an example of numerical values we take the maximum values (maximum absolute values) of the relative sensitivities for the available dimensional ranges in both the MV and the HV/EHV cables:

<u>MV:</u>

$SD_{r,r,max}$= -0.39 (r=4.1mm, w=8.0mm; 50mm^2,18/30kV)
$SD_{R,r,max}$= 0.27 (r=4.1mm, w=8.0mm; 50mm^2,18/30kV)
$SD_{r,w,max}$= -0.93 (r=21,6mm, w=3,4mm; 1000mm^2,6/10kV)
$SD_{R,w,max}$= -1.27 (r=4.1mm, w=8.0mm; 50mm^2,18/30kV)

<u>HV/EHV:</u>

$SD_{r,r,max}$= -0.39 (r=15.2mm, w=30mm; 630mm^2,220/400kV)
$SD_{R,r,max}$= 0.27 (r=15.2mm, w=30mm; 630mm^2,220/400kV)
$SD_{r,w,max}$= -0.87 (r=29.2mm, w=10mm; 2500mm^2,64/110kV)
$SD_{R,w,max}$= -1.27 (r=15.2mm, w=30mm; 630mm^2,220/400kV)

This last value of $SD_{R,w,max}$ indicates, as an example, that for every 1% reduction of the insulation width in this particular cable, the electrical stress at the insulation screen E_R will increase with 1.27%.

As can be seen from the numerical values obtained, the maximum values of sensitivities for the MV cable correspond approximately with the sensitivity values of the cables in the HV/EHV category. This is because maximum values for the relative sensitivities are obtained by a maximum value of *r* in combination with a minimum *w* or vice versa, which means that the not so large available conductor size in the MV case is compensated by the smaller insulation width and vice versa.

MAXIMUM SIZES OF DISCHARGE-FREE DEFECTS IN POWER CABLES

At a given operating voltage, the maximum size of a discharge-free defect can be determined with the help of the Paschen curve, (e.g. [5]), which relates the breakdown voltage to the pressure times gap size. In Figure 4 this Paschen curve is translated to the breakdown electrical stress versus gap size for fixed pressures of 1-4 bar.

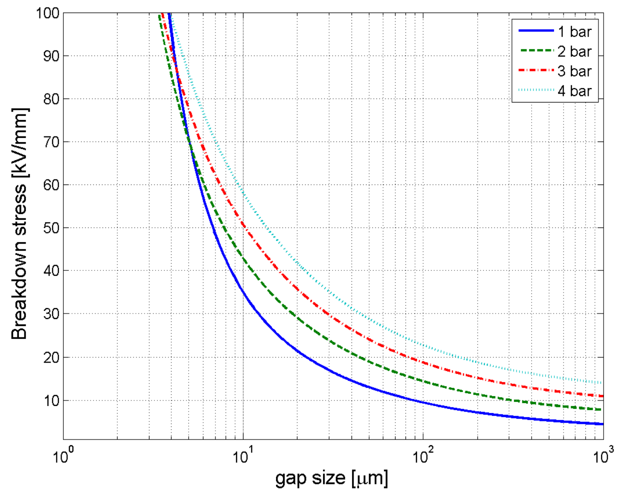

Figure 4: Breakdown field strength in air at 20°C and various pressures

Although causes, locations and shapes of defects in power cables and their accessories can vary in numerous ways, usually they can be generalized into two main common categories:

- spherical (or near) voids within the insulation
- fissures located on the insulation interface

We will further restrict our discussion to these two common defects. The void location at the conductor screen interface represents the worst-case regarding the risk of discharge. Voids represent defects that are typically introduced during the extrusion and curing of the polymeric cable insulation. In case of fissures, those that appear at the insulation screen interface are the most common. They represent defects that are typically introduced during the installation of accessories. The field strength within a spherical void located in a uniform field can be found from the relationship well known in electrostatics [6]:

$$E_v = E \cdot \frac{3\varepsilon}{1+2\varepsilon} \tag{6}$$

where E and ε are the field strength and relative permittivity of the surrounding insulation (XLPE, $\varepsilon = 2.26$). According to equation (6), the electrostatic field enhancement factor in a spherical void cannot exceed the value of 1.5. This upper extreme of 1.5 was used in this paper rather than the value of 1.23 resulting from equation (6) if $\varepsilon = 2.26$. This allows for the fact that shape of the void in practical cable insulation may not be perfectly spherical and that the void is placed in a radial, rather than a parallel electrostatic field.

The field enhancement factor for fissures at the interface to an accessory can be found as a simple ratio of relative permittivities of the insulation material outside the defect and the gas inside the defect (e.g. [6]). Assuming relative permittivity of gas equal to 1, we have:

$$E_f = E \cdot \varepsilon \tag{7}$$

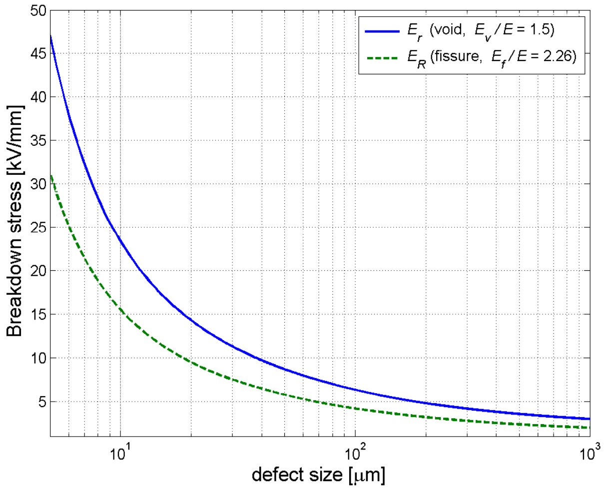

Figure 5: Maximum stress in dielectric (at 1 bar) with no breakdown for voids and fissures at the conductor and the insulation screen respectively

In Figure 5 the resulting maximum stresses before breakdown for both spherical voids at the conductor screen and fissures at the insulation screen are plotted. This graph shows that an approximately 50% stronger field is required to initiate discharges in a spherical void in comparison with a fissure of similar dimension. However, in the radial field of cable insulation, voids may be more vulnerable to discharge inception if they are located at the conductor screen interface as compared to fissures of similar size that are located at the interface with accessory, as the field intensity ratio E_r/E_R can be as high as 3 in some cables.

Additionally, the plots show, as expected, that the higher the field intensity in the dielectric the smaller the size of the defect must be for a discharge free operation of the cable.

Sensitivity of discharge-free defect size to variation of electrical stress

In order to get insight in the sensitivity between the size of a defect for discharge-free operation and the electric stress, we must relate the relative changes of both parameters again. For this purpose we define the relative sensitivity S of defect size to electric stress change as:

$$S = \frac{d(d_{gap})/d_{gap}}{dE_i / E_i} \tag{8}$$

where d_{gap} is the defect size and E_i the electrical strength inside the defect. The relationship between the *breakdown* stress E_{bd} and the defect size is given by Figure 4 and Figure 5. S is calculated by taking the derivative of these functions and normalise this on d_{gap} and E_{bd}. Due to the fact that E_{bd} and E_i are related through a constant field enhancing factor (1.5 for voids and 2.26 for fissures), normalisation of the parameters causes $dE_i/E_i = dE_{bd}/E_{bd}$. Figure 6 shows the resulting relative sensitivity, depending on the defect size for various gas pressures.

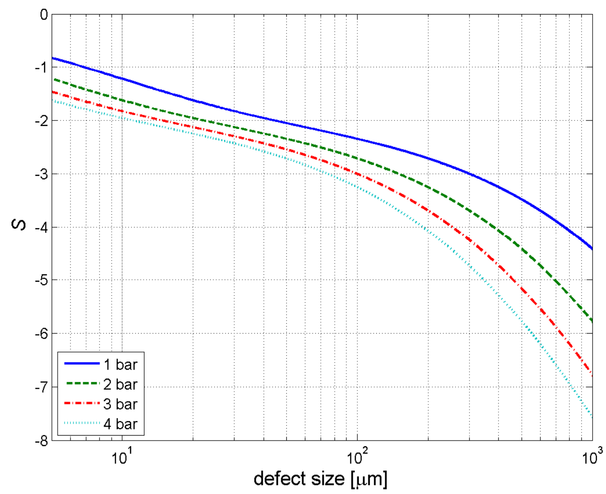

Figure 6: Relative sensitivity of defect size to relative electric field change for discharge free operation

The plots in this figure indicate that, for example, for a defect size of 100 µm, and a gas pressure of 1 bar, the value of the relative sensitivity S, is equal to -2.35, meaning that a 1% increase of the electric stress would require a 2.35% decrease of allowable defect size in order to maintain discharge-free operation.

RISKS OF PARTIAL DISCHARGES IN CABLE SYSTEMS

Combination of the relationships between cable design (voltage and dimensions) and electrical stress on one hand

and electrical stress and maximum allowable size of discharge-free defects on the other hand, gives the relationship between design and permissible defect size. Figure 7 depicts the inception voltages for spherical voids at the conductor screen for the most common rated cable voltages. The worst-case dimensions, i.e. the dimensions leading to maximum electric stress at the conductor screen, are used for the different voltage levels (minimum insulation width and minimum conductor size). It is usually recommended that cables are tested (PD tests) with voltages of $1.7U_0$. These levels are therefore used in Figure 7. The indicated crossings show the maximum permissible defect sizes. Considering the entire range of voltages, the PD-free defect size varies from 132µm for 6/10kV to 5.95µm for 220/400kV cables. If nominal voltages are used (not plotted here) the range is from 663 to 10.8µm respectively.

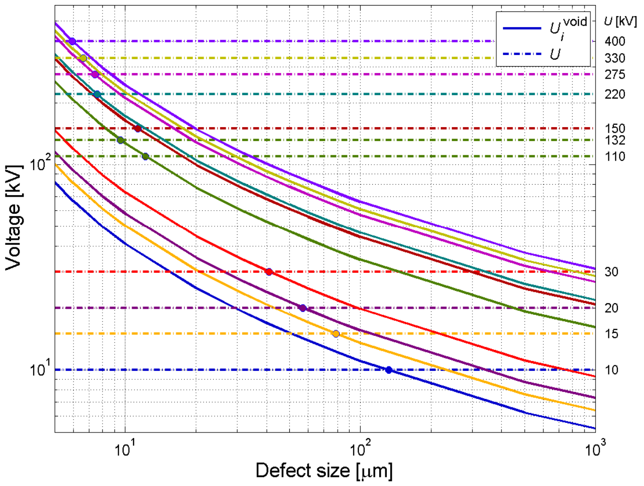

Figure 7: PD inception voltage at U (1 bar) as a function of size of a spherical void located at the conductor screen

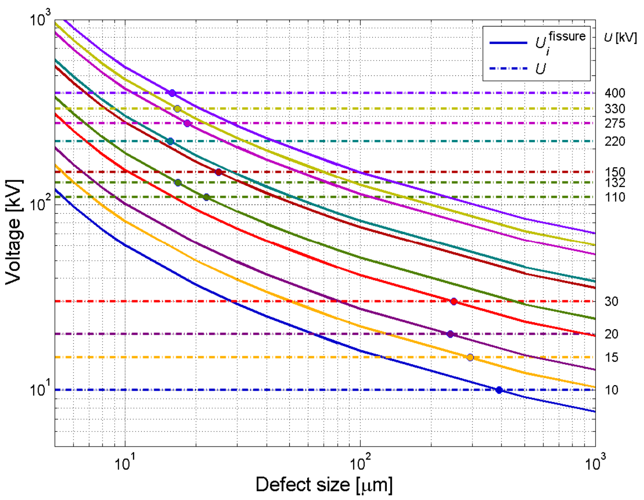

Figure 8: PD inception voltage at U (1 bar) as a function of size of a fissure located at the insulation screen

Figure 8 shows similar plots of inception voltages in the case of fissures at the insulation screen. The dimensions leading to the largest electric stress at the insulation screen are also chosen in this case, namely, the minimum insulation width combined with the maximum conductor size. It is clear that at this location the permissible defects sizes are larger (390µm for 6/10kV to 15.8µm for 220/400kV cables). However, imperfection at the interface with accessories are typically larger too, since they are caused by the less controllable process of manual installation.

The results of these calculations can be used to predict whether PDs will occur with a specific manufacturing process that produces defects according to some maximum size. This method can also be used to specify the permissible defect sizes a certain cable design. Typically, the presence of discharging voids within the cable insulation will be detected during routine tests after production of the cable. The presence of fissure type defects at interfaces with an accessory should be detected by tests after installation.

RISKS FROM DESIGN MODIFICATION AND RANGE OF TYPE APPROVAL

If the dimensions in a cable design are changed, the electrical stress inside the dielectric is also changed. The earlier sections in this paper describe sensitivity of change of electric field to dimensional change. Subsequently, the electric field change causes a change in permissible defect size in the insulation. The combination of both sensitivities leads to the rate of change of permissible defect size as a function of small variations in dimension (Δr and/or Δw) as follows:

$$\Delta d_r = S \cdot SD_{(R,r),r} \cdot \Delta r \qquad (9)$$

$$\Delta d_w = S \cdot SD_{(R,r),w} \cdot \Delta w \qquad (10)$$

This provides for a generalised way to evaluate the effect of the dimensional change without the need for calculating the specific electric field values.

We apply the above method to specific examples to illustrate its use. In the first example, we assume a design change of a 110kV, 1000mm² cable such that the insulation thickness is decreased from 10mm to 8mm. Without having to calculate electrical fields, we can see from the plotted graphs that for the void size at the conductor screen:

$SD_{r,w}$ = -0.785 , S = -1.34 → Δd_w^{void} = -21%

and for a fissure at the insulation screen:

$SD_{R,w}$ = -1.18 , S = -1.68 → $\Delta d_w^{fissure}$ = -40%

meaning that a reduction of insulation thickness by 20% results in a reduction of permissible spherical void size at the conductor screen by 21% and a reduction of allowable fissure size at the insulation screen by 40%.

An interesting case is the application of this method on the range of type approval in the IEC 60840 and IEC 62067. The relevant clauses state that once type tests have been successfully performed on one or more cable systems of a specific rated voltage and construction, the type approval may be valid for a re-dimensioned cable system if, apart from a few others, the following conditions are satisfied:

- the conductor cross-section is not larger than that of the tested cable system
- the calculated nominal electrical stress at the cable

conductor screen in the new system does not exceed the conductor screen stress of the approved cable system by more than 10%;

- o the calculated nominal electrical stress at the cable insulation screen does not exceed that of the tested cable system;
- o the calculated nominal stresses at cable-accessory interfaces do not exceed those of the tested cable system

An increase of conductor cross-section results in an increase of stress at insulation screen interface if the insulation thickness is maintained, which is normally the case. Current standards would require type testing of the redesigned cable system in case of such modification. An increase of the conductor cross-section by one level leads in the worst case to a 18% stress increase in HV and EHV cables when the conductor cross-section is changed from 2000 mm^2 to 2500 mm^2. From Figure 6 it can be observed that, depending on the voltage and therefore original PD-free defect size, the allowable fissure size at the insulation screen should be decreased by a factor 2-4. This means that if the level of precision of the accessories assembly is maintained there is no longer a guarantee for a discharge-free operation. Furthermore, it should be pointed out, that the range of type approval clause is not solely based on dielectric stress considerations. An increase of conductor size also causes greater mechanical stresses in the cable system structure during e.g. thermal cycling.
An increase of dielectric stress on the conductor screen occurs either when the conductor cross-section is decreased or the insulation thickness is decreased. It can be shown that in order to achieve a 10% increase of stress, the thickness of insulation must decrease 10-15%. The influence on the maximum defect size is subjected to an extra multiplication factor, S, which depends on the voltage level.

The systematic analysis of risk of partial discharge inception presented in this paper shows origins of range of type approval requirements. A few simple examples shown above demonstrate that dimensional change beyond the current standard recommendations can increase the risk of partial discharge by an unacceptable degree. This methodology formed the bases for the conclusions reached by the Cigré WG B1-06 which did not recommend relaxing current requirements of the range of type approval [1].

CONCLUSIONS

This paper shows a coherent methodology for analysing the risk of partial discharge inception in high voltage cable insulation. Spherical voids located at the conductor screen interface and fissures located at the insulation screen interface are analysed. From the point of view of cable system technology, these two types of insulation defects represent two most important practical cases. The results obtained show for example that at test voltage, $1.7U_0$, the permissible size of spherical voids ranges approximately from 132μm for 6/10kV to 5.95μm for 220/400kV cables. For fissures at the insulation shield interface this range is between 390μm for 6/10kV and 15.8μm for 220/400kV cables.

Additionally, this paper presented the impact of modifications of insulation dimensions on the risk of discharge development in defects according to their size. The approach was based on the notion of sensitivity of dielectric stress to dimensional change of cable insulation and the notion of sensitivity of size of discharge free defect to the change of electric field intensity. The numerical results obtained can be interpreted qualitatively by stating that if design modifications result with an increased level of electrical stress then larger proportions of fissures and voids present in the cable will develop partial discharges at given voltage level. In order to avoid an increase to discharge activity, the quality of cable insulation manufacture and precision of accessories assembly must follow such design modifications.

The methodology presented in this paper shows the origins of some of the foundations of the Range of Type Approval clauses contained in IEC60840 and IEC62067. It was recently utilised by the Cigré Working Group B1-06 in recommending of revision of these standards [1]. They recommended the Range of Type Approval in these standards should not be broadened.

REFERENCES

[1] WG B1.06, "*Revision of qualification procedures for high voltage and extra high voltage AC extruded underground cable systems*", Cigré Technical Brochure 303, Electra 227 page 30-39, August 2006

[2] P. C. J. M. van der Wielen, E. F. Steennis, P. A. A. F. Wouters, "*Fundamental Aspects of Excitation and Propagation of On-line Partial Discharge Signals in Three-phase Medium Voltage Cable Systems*", IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 10, No. 4; 2003, pp. 678-688

[3] F. C. Cheng, "*Insulation Thickness Determination of Polymeric Power Cables*", IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 1, No. 4, 1994, pp. 624-629.

[4] A. Nouar, M. Guibadj, I.K. Lefkaier, A. Boubakeur, "*Numerical study of partial discharges apparition in XLPE insulation of high voltage cables*", Vol. 3, Power Tech Conference Proceedings, 2003 IEEE Bologna. Intemational Symposium on Electrical Insulation, Boston, MA USA, April 7-10,2002. pp. 91-95.

[5] T.W. Dakin, G. Luxa, G. Oppermann, J. Vigreux, G. Wind, H. Winkelnkemper, "*Breakdown of gases in uniform fields – Paschen curves for Nitrogen, air and sulphur hexafluoride* ", Electra No. 32, 1974, pp. 61-74

[6] F.H. Kreuger, "*Industrial High Voltage: Fields, Dielectrics, Construction*", Delft University Press, 1991.